PUBLICATIONS
OF THE
Astronomical Society of the Pacific.

Vol. XXXI. San Francisco, California, July, 1919 No. 182

ON THE SOURCES OF STELLAR ENERGY[1]

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Dr. Shapley's stimulating note[2] (which he kindly communicated to the writer in advance of its publication), suggests the communication of some results of a study of the same topic which is still in progress.

1. The strongest evidence against the hypothesis that the rate of radiation from a hot body to space is considerably less than it would be to a material enclosure at the absolute zero is found in the present state of the Earth. According to Abbot (*Proc. Nat. Acad.*, **4**, 104, 1918), the energy which the Earth actually receives from the Sun, after allowance for reflection back into space, amounts, on the average, to 0.29 calories per square centimeter per minute over the whole surface. The mean temperature of the surface is 287° Abs, to which corresponds a black-body radiation of 0.55 cal/cm^2/min. The temperature of the effective radiating surface of the Earth is considerably lower than this, since much of the outgoing radiation comes from the upper atmosphere, and it is probable that neither the actual surface nor the atmosphere is a perfect radiator.

It follows that the ratio of the rate at which the Earth actually radiates heat to space to the rate at which it would radiate to a surrounding material enclosure at the absolute zero is much greater than 0.29/0.55—that is, much greater than 0.53, and there is no evidence that it is less than unity. But the ratio which would be required to reconcile the probable ages of the Sun and stars with a purely gravitational supply of energy is of the order of magnitude of 0.001. Unless, then, we make the extremely unsatisfactory assumption that the law of radiation from a hot body to *empty space* is entirely different for the long waves emitted by the Earth and the short waves emitted by the Sun, we appear to be shut up

[1]Presented at the Pasadena meeting of the *Ast. Soc. Pac.*, June 19, 1919.
[2]*Publications of the Ast. Soc. Pac.*, June, 1919.

to the conclusion that the Sun and stars have actually radiated during their active life, many times more energy than would be liberated by gravitational compression during their contraction from infinity.

2. It must therefore be assumed that there exists within the stars some unknown store of energy of enormous magnitude, which is made available to supply the heat lost by radiation. Tho the nature of the process by which this energy is transformed is unknown, we do know that it must satisfy certain conditions:

(*a*) It must generate large quantities of heat per unit mass in the interior of the stars, and very little or none under laboratory conditions, or in the interior of the Earth.

(*b*) It must not be liable to accelerate its own rate so as to end in an explosive catastrophe, for the stars in general appear to be very stable, and the phenomena of Novae are apparently superficial rather than deep-seated.

(*c*) It must in some way be regulated so as to supply heat to each star at almost exactly the rate at which the star radiates heat to space, for the rate of energy transformation in the processes of stellar evolution is evidently exceedingly slow.

(*d*) It must ultimately die down as time goes on, making it possible for a star to proceed to the dwarf stages in which its radiation is small.

(*e*) A sufficient amount of energy must still be available in these later stages to permit them to be of very long duration, for the large majority of the stars per unit of volume are dwarfs.

3. Some of these conditions are easily met. For example, (*a*) leads to the assumption that the process operates at a perceptible rate only under extreme conditions of temperature or pressure, such as prevail in the interior of the stars. Condition (*d*) is sufficiently met by assuming that the energy is derived from some finite store which is gradually exhausted, and that the rate of transformation falls off as the remaining supply decreases. This hypothesis leads naturally to the further consequence that complete exhaustion will be approached asymptotically, and hence satisfies condition (*e*).

But conditions (*b*) and (*c*) present serious difficulties. If the hypothetical process is to satisfy condition (*a*), the rate at which it takes place must have a positive temperature coefficient. But if this is true, why does not the process, when once started,

steadily raise the temperature, and so accelerate its own rate, until it culminates in an explosion of tremendous proportions? And what can be the mechanism which not only prevents this, but automatically adjusts the rate of transformation of this enormous store of internal energy to exactly the rate required to meet the loss by radiation? To add to the complexity there is good evidence that among the giant stars the rate of radiation (Eddington's bolometric magnitude) varies very little with the density among stars of the same mass, but that the total radiation *per unit of mass* is considerably greater for the more massive stars.

4. It does not appear to have been noticed that a simple explanation of these difficulties may be found in the fact that a sphere of perfect gas, in equilibrium under its own gravitation, has as a whole *a negative specific heat.* If such a mass passes thru a series of "homologous" configurations, its temperature rises, according to Lane's Law, as it contracts, while at the same time its total store of energy diminishes. If heat should be supplied to the interior of such a star, it would expand and its temperature would fall—the amount of energy expended in expanding against gravity being greater than that supplied in the form of heat. This apparently paradoxical behavior is closely analogous to certain other cases where other forms of energy are transformed into gravitational potential energy, for example, to the acceleration of a comet's mean motion by a resisting medium. Tho the simple model of the sphere of perfect gas passing thru a series of homologous states may not exactly represent the facts, it is evident that the possession of a negative effective specific heat is an essential property on any theory of a giant star which contracts and rises in temperature while losing heat by radiation. Without this property, such a star would be incapable of supplying its radiation losses by means of gravitational contraction.

To this must be added the assumption that the rate at which a star can get rid of heat of deep-seated origin by radiation depends upon its mass, its density, and the opacity of the material of which it is composed. This conclusion has been reached theoretically by Eddington, on the basis of certain simplifying assumptions, and by Jeans, on another set of postulates. Both agree that the total radiation of a giant star should be almost independent of its density. For the present purpose, the exact validity of the assumptions made by either investigator is unimportant so long as it is

assumed that their conclusions correctly represent the general course of the actual phenomena. This assumption is strongly supported by the observed characteristics of the giant stars, which also indicate that the coefficient of opacity is surprisingly similar in different stars.

5. Suppose now that there is a large mass of gas of very low density, and in equilibrium under its own gravitation. At first its temperature will be relatively low thruout, and it will have to depend on gravitational contraction to supply the energy lost by radiation. It will contract at a relatively rapid rate, and its temperature will rise. As its central regions reach the critical temperature at which the evolution of heat by the "unknown process" postulated above becomes sensible, this supply will begin to supplement the heat due to contraction. The rate of radiation, being determined almost entirely by the mass and opacity, will remain nearly constant, but, as the temperature of the interior rises, more and more of this outgo will be supplied by the "unknown process" and the rate of contraction will become very slow, so that the further rise of central temperature will be checked. Should this temperature rise too high so that heat was produced faster than it could be radiated away, the star would expand, its temperature would diminish, and the supply of heat would be partially cut off; but if the central temperature fell too low, too little heat would be generated, the star would contract, its temperature would rise, and the internal supply of heat would be augmented. It is clear that an approximately steady state will be reached in which just enough of the material in the interior of the star is just hot enough to supply, by the "unknown process," the amount of heat needed to support the radiation. The law of distribution of temperature, density, etc., thruout the mass will differ somewhat in this state from that which prevailed when the energy was derived from contraction, but the new state will be stable, not only with respect to changes in the distribution of matter, but also with respect to variations in temperature and in the rate of generation of heat.

The duration of this stable state will be conditioned by the supply of energy available from the "unknown" source, and may be very great. As this supply, however, becomes gradually exhausted, more and more of the interior of the star will have to be heated above the critical temperature in order to keep up the supply of heat from the impoverished material, and the average

temperature of the interior will rise. These changes will be accompanied by a contraction of the star, and an increase of its effective surface temperature, so that it will pass slowly along the series of giant stars. The series of states thru which it will pass will not be "homologous" since the fraction of the mass which is involved in the transformation of the "unknown" energy steadily increases; but, qualitatively, its evolutionary progress will be similar to that of a mass dependent upon contraction for its energy, reaching a maximum effective temperature at a density considerably less than that of the Sun, and then following the series of dwarf stars. The rate at which these changes take place will, however, be very much slower, and the relative intervals of time required to pass thru corresponding stages may be different. It is easy to see that, in comparison with a star which derives its energy from contraction, the giant stages will occupy a greater proportional interval (since most of the great store of energy is transformed during these stages). The dwarf stages, however, will still occupy more time than the giant stages, since the rate of transformation of energy is so much smaller.

6. The hypothesis thus sketched in outline appears to meet the outstanding difficulties (*b*) and (*c*), and to afford a reasonable solution of the problem of the source of stellar energy. Several remarks may be made regarding it.

First, the only assumptions that have been made regarding the "unknown source" of energy are: that the energy supply is finite, tho great, and that the rate of its transformation into heat depends upon the amount still available for transformation, and increases steadily with the temperature of the medium in which the transformation takes place. These properties are so general that they convey little information regarding the nature of the process; but it is obvious that almost any of the sources which have so far been suggested—such as atomic disintegration or mutual neutralization of positive and negative electric charges—would meet the conditions. The present argument has, however, been purposely kept clear from discussion of the details of any such hypothesis.

Second, this hypothesis suggests for the internal constitution of a giant star: (1) a nucleus, for which the temperature is above the critical limit where the liberation of energy by the "unknown process" becomes sensible and within which practically all the energy required to maintain the surface radiation is liberated,

and (2) an outer shell of lower temperature, in which very little heat is produced, but which is in a state of radiative equilibrium and conditions the rate at which the internal energy can reach the surface and escape into space. The problem of determining the law of distribution of density or temperature within such a body, tho perhaps difficult, is doubtless capable of solution by known methods.

Third, it is of much interest to note that the hypothesis outlined above presents a direct explanation for two astrophysical facts that have so far been hard to account for. The first of these is the remarkable infrequency of occurrence of very red giant stars. Stars with a color index exceeding two magnitudes are practically unknown (except in the branch series which includes the spectral classes R and N and apparently represents exceptional conditions involving only a small proportion of all the stars). On the contraction hypothesis, the apparent absence of stars in a state antecedent to the familiar and fairly abundant Class M is very puzzling; but on the new hypothesis it is only necessary to assume that the interior of a giant star does not reach the temperature at which the supply of heat from the "unknown source" is important until its effective surface temperature has reached the value characteristic of Class M. Stars in earlier states of evolution would then run thru their course so rapidly that there would be very few of them in a given region of space at any one time, and their rarity is thus accounted for. The second is the maintenance of variability of the Cepheid type. It now appears probable that the cause of this variability is some form of pulsation, involving a bodily contraction and expansion of the star, with corresponding changes in temperature. Eddington has shown that the "leakage" of heat from the hotter to the colder regions of the star's interior would tend to damp out such pulsations within a few thousand years at most. But the process suggested above supplies heat to the interior at the greatest rate just when and where it is hottest, and would thus tend to make good the "leakage." It seems probable, therefore, that in such a process may be found the driving force which maintains Cepheid variation. On this hypothesis the liberation of heat would take place mainly when the star was smallest and hottest (internally, at least). This supply of heat in periodic "impulses" may have some connection with the asymmetry of the light and velocity curves.

The singular relation which connects the period and the absolute magnitude of Cepheids may perhaps also find an explanation in this hypothesis. It is pretty clear, from astronomical evidence, that Cepheid variation is something which occurs at a definite stage in the evolution of a star, and that the density at which it is developed varies with the mass of the star, and is lower the greater the mass. Let it now be assumed that the occurrence of Cepheid variation is dependent upon some relation between the size of the heat-producing nucleus and the remainder of the star. Stars of large mass will have a higher central temperature for the same density; the formation of such a nucleus will therefore begin in them at a lower density than in stars of smaller mass and, at the same density, the nucleus will be proportionally larger. The assumed relative size of the nucleus will therefore be reached at a density which is definite for any assigned mass, but is lower the greater the mass.

Princeton University Observatory,
June 9, 1919.